Tunneling conductance of normal metal/insulator/Sr_2RuO_4 junction

Masashi Yamashiro and Yukio Tanaka

Graduate school of Science and Technology, and Department of Physics, Niigata University, Ikarashi Niigata 950-21, Japan

Satoshi Kashiwaya

Electrotechnical Laboratory, Tsukuba, Ibaraki 305, Japan

A theory of tunneling conductance spectra for normal metal/insulator/Sr_2RuO_4 junction is studied theoretically. We assume several types of pair potentials with triplet symmetries that are promising candidates for Sr_2RuO_4. The calculated conductance spectra show either zero bias peaks or gap like structures depending on the orientations of the junctions. The existence of a residual components in the gap reflects a non-unitary property of the superconducting states. Based on the calculation of a temperature dependence, we will verify that the measurement temperature below 100mK is required to determine the pairing symmetry experimentally.

1. Introduction

Recently, Maeno *et. al.*[1] discovered a superconducting state in Sr_2RuO_4. Since this material has layered perovskite structure, strong anisotropic properties in electronic states are expected for both normal and superconducting state[2]. Several experiments indicate that rather large residual density of states remain even at low temperatures [1, 3]. Moreover, the existence of the ferromagnetic spin fluctuations is supported by several evidences [4, 5]. Based on these facts, two-dimensional nonunitary triplet superconducting states which belong to two-dimensional odd-parity E_u representation under the tetragonal symmetry have been suggested theoretically [6, 7]. However, a definitive evidence for the triplet symmetry states has not been presented so far. Therefore, more precise and detailed experiments are expected to get a clear conclusion.

Tunneling spectroscopy is one of the candidates for such experiments because of its high energy resolution. Moreover a phase sensitive capability of tunneling spectroscopy has been revealed [8, 9]. However, no theory exists for tunneling spectroscopy for triplet superconductors even now. In this paper, we study the tunneling conductance spectra for normal metal / insulator / Sr_2RuO_4 (N/I/S) junction in the finite temperature region by extending the previous theories [8, 9, 10]. The transition temperature T_C of 1.04K is assumed in the following.

2. Model

For the calculation of the tunneling conductance, we assume an N/I/S junction model in the clean limit with a semi-infinite structure. A nearly two-dimensional Fermi surface is assumed. We calculate the conductance for two kinds of orientations with completely flat interfaces; one is perpendicular to the x-axis and the other is perpendicular to the z-axis. The Fermi wave number and the effective mass are assumed to be equal both in the normal metal and in the superconductor.

Hereafter, following the discussion by Sigrist[6] and Machida [7], we will choose two kinds of nonunitary pair potentials with tetragonal symmetry. The pair potential forms are $\Delta_{\uparrow\uparrow} = \Delta_0 \times \sin\theta(\sin\phi + \cos\phi)$ and $\Delta_{\uparrow\uparrow} = \Delta_0 e^{i\phi}\sin\theta$, that are referred to as $E_u(1)$ and $E_u(2)$, respectively. Here $\Delta_{\uparrow\uparrow}$ is ($\uparrow$, $\uparrow$) component of the pair potential matrix in the spin space, and Δ_0 is the amplitude of the pair potential in the bulk state. The details of the calculation for the conductance formula and results at zero temperature are already discussed in Ref.[10]. Here, we extend previous results to finite temperature cases. The conduc-

tance formula for z-y plane interface is given by

$$\sigma_S(eV) \propto \frac{1}{T}\int_{-\infty}^{\infty}\int_{\pi/2-\delta}^{\pi/2}\int_{-\pi/2}^{\pi/2}(\sigma_{S,\uparrow}+\sigma_{S,\downarrow})\sigma_N$$

$$\times \mathrm{sech}^2\left(\frac{E-eV}{2k_BT}\right)\sin^2\theta\cos\phi d\theta d\phi dE$$

$$\sigma_N(eV) \propto \frac{2}{T}\int_{-\infty}^{\infty}\int_{\pi/2-\delta}^{\pi/2}\int_{-\pi/2}^{\pi/2}\sigma_N \mathrm{sech}^2\left(\frac{E-eV}{2k_BT}\right)$$

$$\times \sin^2\theta\cos\phi d\theta d\phi dE$$

$$\sigma(eV) = \frac{\sigma_S(eV)}{\sigma_N(eV)} \quad (1)$$

The quantity $\sigma_{S,\uparrow(\downarrow)}$ is obtained in a similar way at zero temperature using the coefficients of the Andreev reflection and normal reflection, where σ_N is the tunneling conductance in the normal state. The quantity δ expresses the degree of the two-dimensionality of the Fermi surface which is chosen as 0.05π. The conductance formula for the x-y plane interface is obtained in a similar way.

3. Results

The calculated conductance spectra $\sigma(eV)$ are plotted for various temperatures and barrier heights. For all cases, due to the nonunitary property of the pair potential, $\sigma(eV)$ is definitely larger than 0.5. As seen from [Fig.(1)] to [Fig.(4)], with the increase of temperature, $\sigma(eV)$ becomes nearly constant. The temperature dependence is significant in the case of $Z=5$ both for $E_u(1)$ and $E_u(2)$ states. For $\mathrm{E}_u(1)$ state, $\sigma(0)$ is enhanced at low temperatures in the z-y plane junctions as shown in Fig.(2). In this direction, $\sigma(0)$ of $\mathrm{E}_u(2)$ state converges to a nonzero value at zero temperature. This difference is due to the fact whether zero energy states at the interface are formed on the finite area of the Fermi surface or the line of the Fermi surface. In the large Z limit, zero energy states (ZES) are expected for $-\pi/4 \leq \phi \leq \pi/4$ in the case of $\mathrm{E}_u(1)$ state. While ZES are expected for $\phi = 0$ in the case of $\mathrm{E}_u(2)$ state.

In the case of x-y plane interface junction, gap-like spectra are obtained. The difference of the conductance spectra between $\mathrm{E}_u(1)$ state and $\mathrm{E}_u(2)$ state is clearly seen below $T \leq 0.1T_C$ and Z=5.

In conclusion, to determine the symmetry of pair potential in Sr_2RuO_4, tunneling spectroscopy measurements will give us definitive information if the measurements will be performed at a temperature lower than 100 mK and by using highly controlled junctions.

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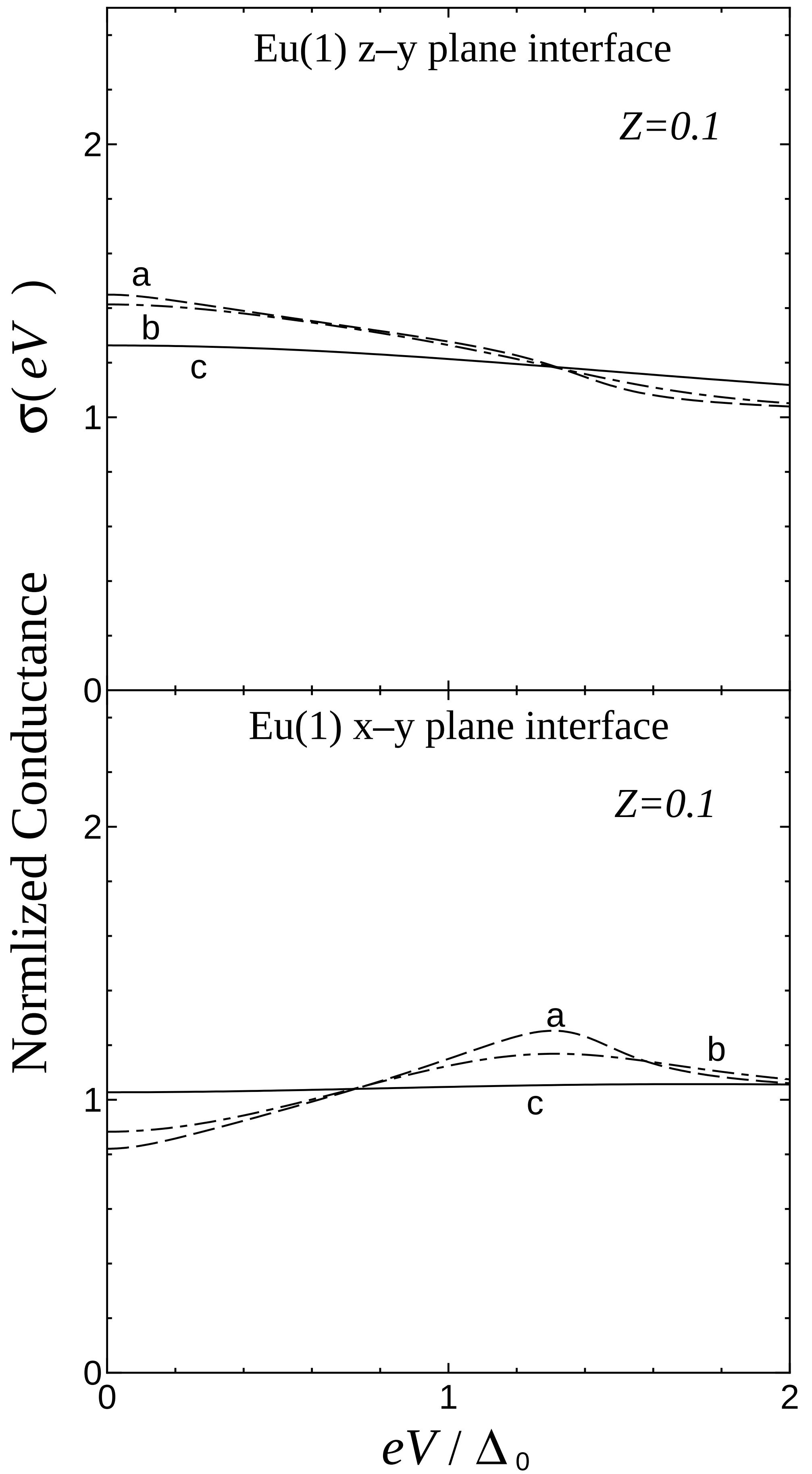
Figure 1: $\sigma(eV)$ is plotted as a function of eV/Δ_0, with a:T=0.1T$_c$, b:T=0.3T$_c$, and c:T=0.8T$_c$.

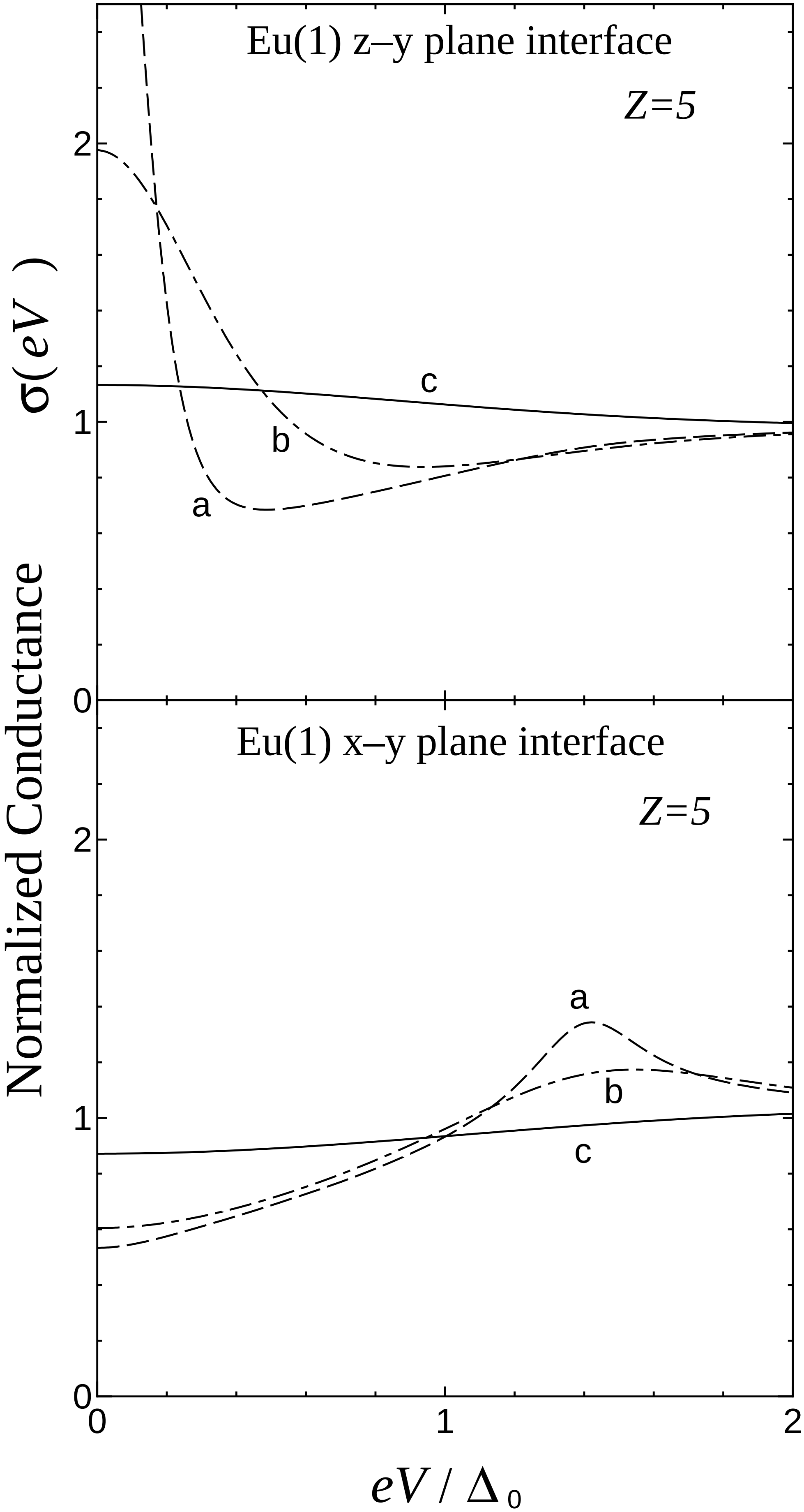
Figure 2: $\sigma(eV)$ is plotted as a function of eV/Δ_0, with a:T=0.1T$_c$, b:T=0.3T$_c$, and c:T=0.8T$_c$.

Figure 3: $\sigma(eV)$ is plotted as a function of eV/Δ_0, with a:T=0.1T$_c$, b:T=0.3T$_c$, and c:T=0.8T$_c$.

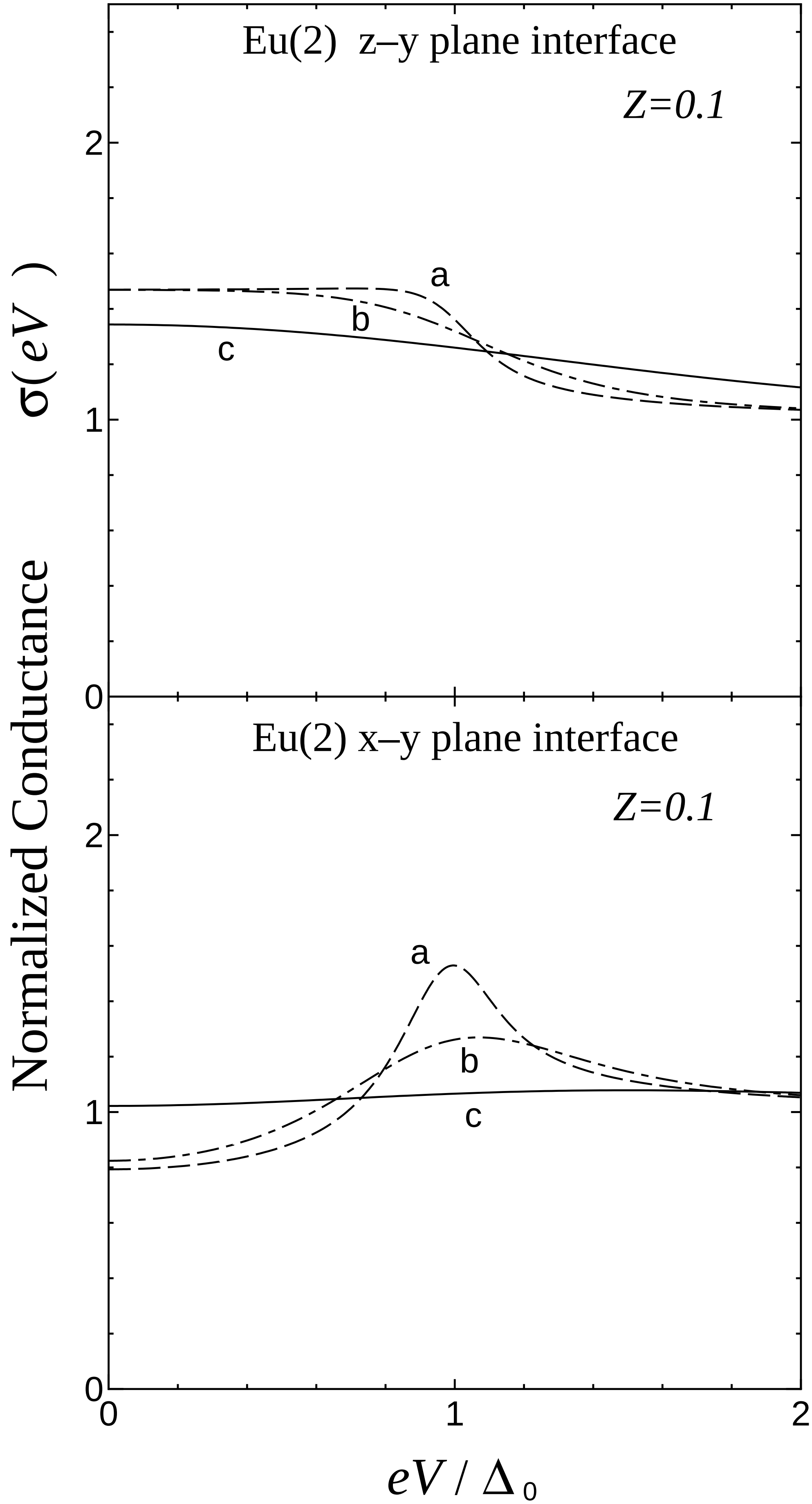
Figure 4: $\sigma(eV)$ is plotted as a function of eV/Δ_0, with a:T=0.1T$_c$, b:T=0.3T$_c$, and c:T=0.8T$_c$.



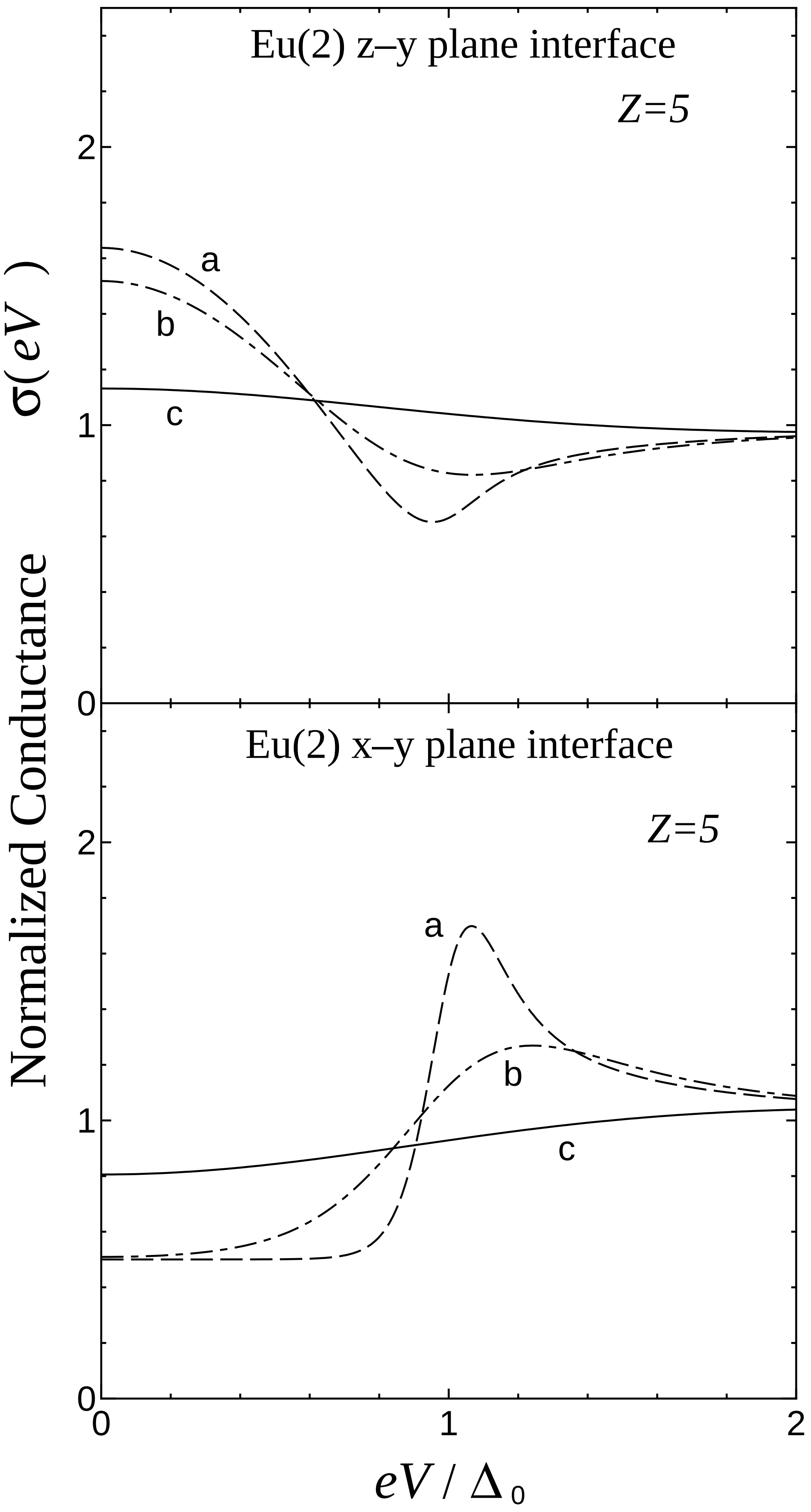
Yamashiro, figure1



Yamashiro, figure2



Yamashiro, figure3



Yamashiro, figure4